

The “115” Superconductors

Eric Bauer

Fedor Balakirev

Xin Lu

Marc Janoschek

Roman Movshovich

Joe Thompson

Vladimir Sidorov

Jianxin Zhu

(LANL)

Soonbeom Seo

Tuson Park (SKKU)

Zach Fisk (UC Irvine)

Philip Moll (ETH)

Hiro Sakai (JAEA)

Hiroshi Yasuoka (JAEA)

Luis Balicas (NHMFL)

Filip Ronning

Los Alamos National Lab

Outline:

- **115 heavy fermion primer**
- **Non-universality of dopants (Cd vs. Sn doping)**
 - **Influence on quantum criticality and superconductivity**
- **High Magnetic Field Study of CeRhIn₅**
 - **Competing Density wave**
 - **Gigantic anisotropy**

Superconductivity in Heavy Fermions

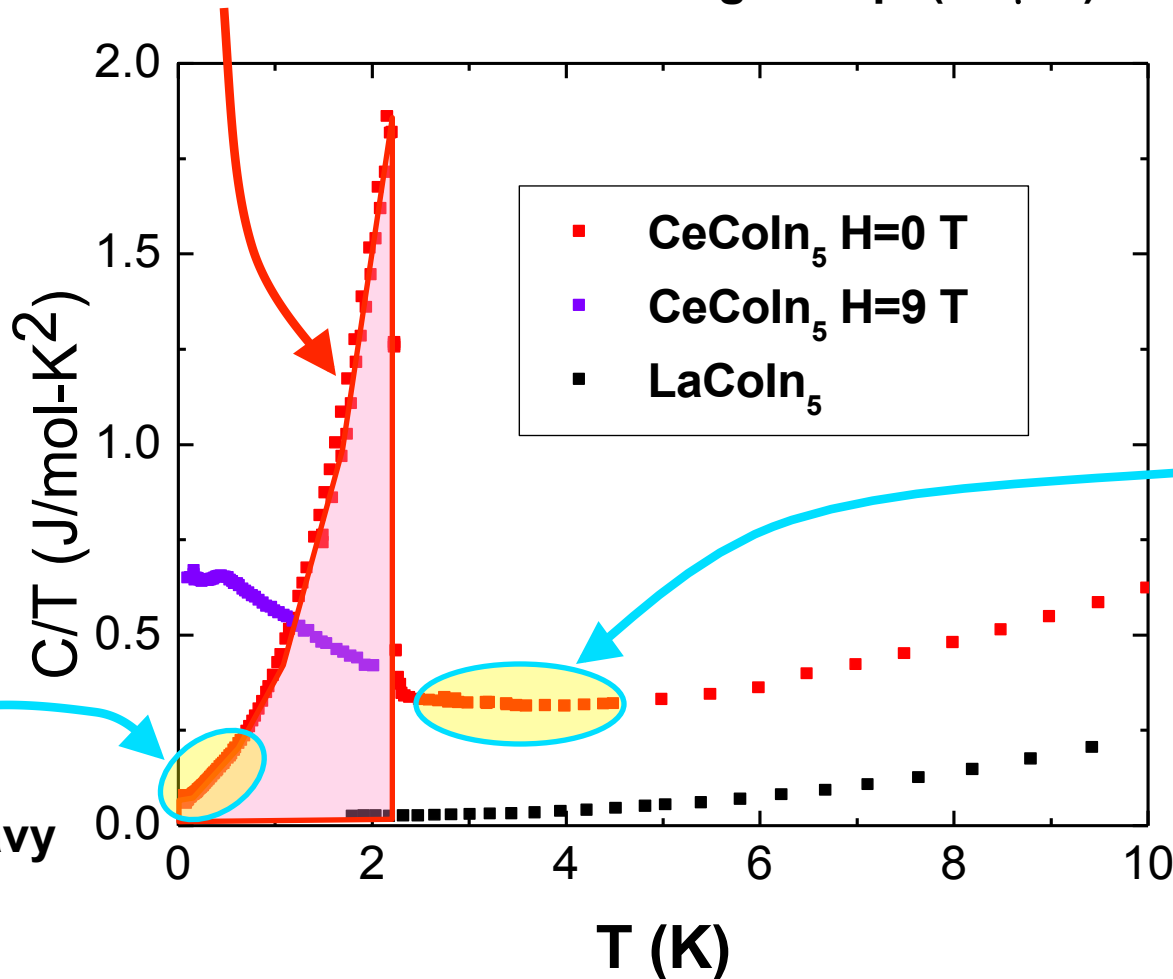
- Large entropy goes into the SC state

- Stoichiometric → high purity, large m.f.p. ($> 1\mu\text{m}$)

• Dirac Materials



- Nodal QP's
- that are heavy



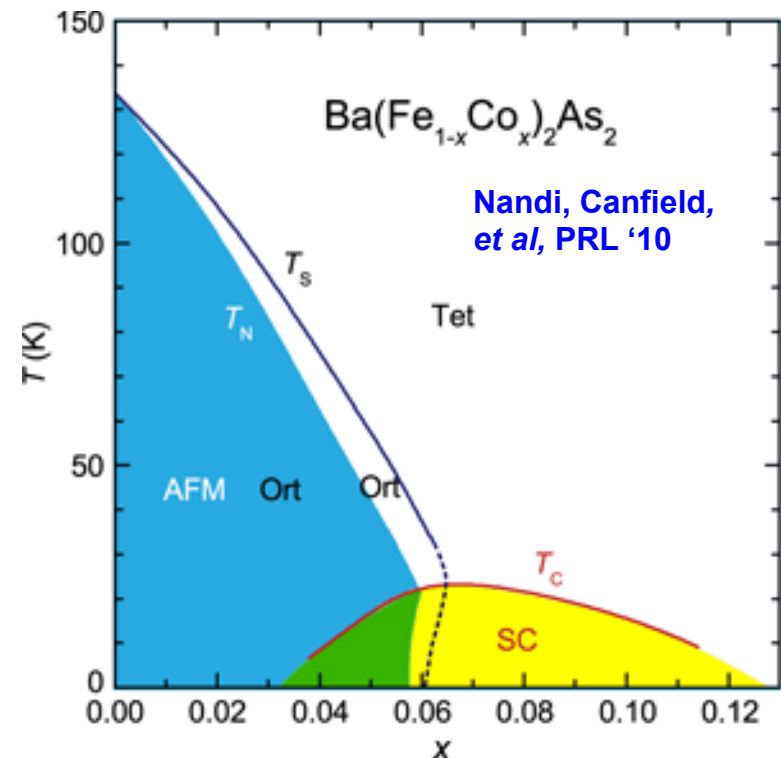
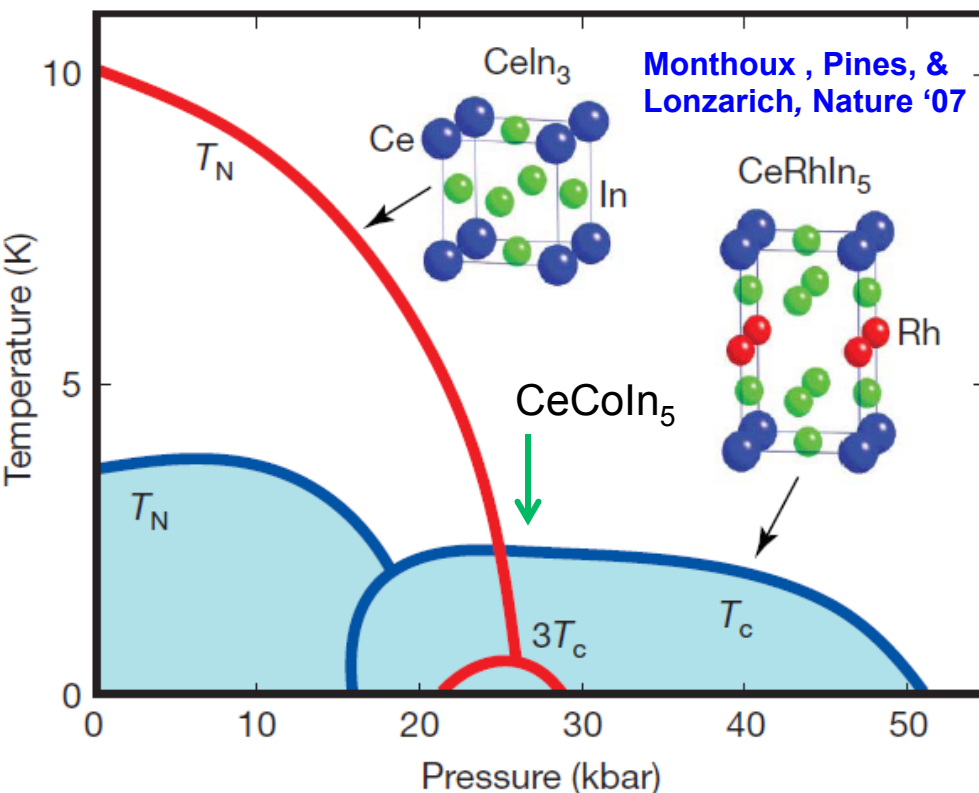
- Heavy Electrons

$$\frac{C}{T} \propto m^*$$

- small energy scale → highly tunable

- T_c/T_F similar to cuprates

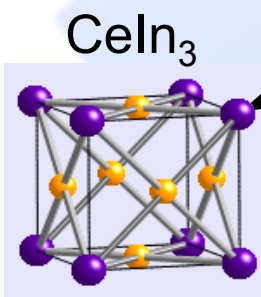
SC in proximity to Antiferromagnetism



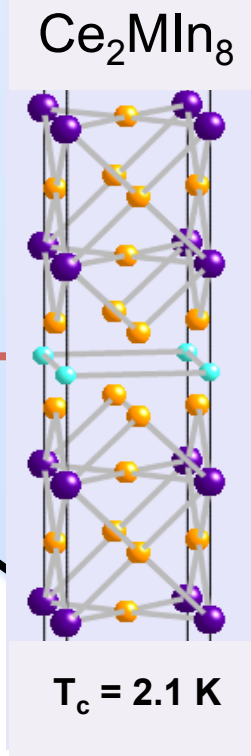
- Phase diagram generic for **Cerium** heavy fermion SC's
- Parent compound is an AF metal
- $T_c/T_F \sim 0.1$
- SC is unconventional (power laws/sign changing OP)
- Tunable with doping or pressure.
- Spin Fluctuations...

Reducing Dimensionality

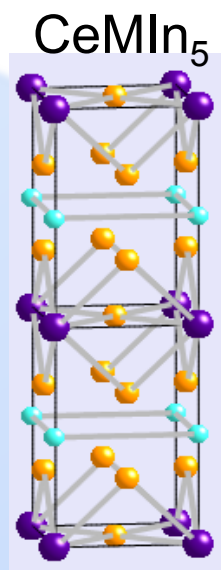
Increasing Bandwidth



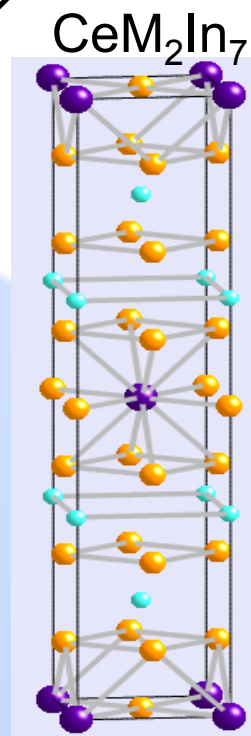
$T_c = 0.2 \text{ K}$



$T_c = 2.1 \text{ K}$

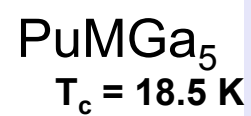
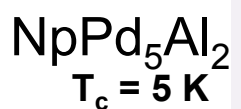


$T_c = 2.3 \text{ K}$



13 compounds in this family are superconductors

Increasing T_c
100 x



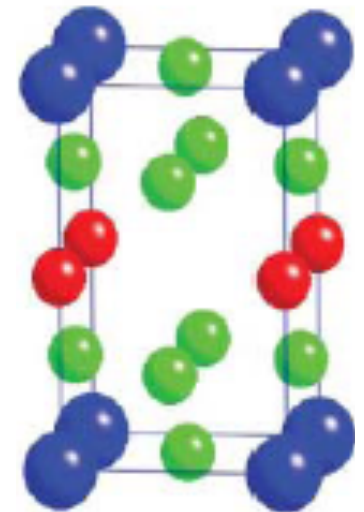
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Cd vs Sn doping in the 115's

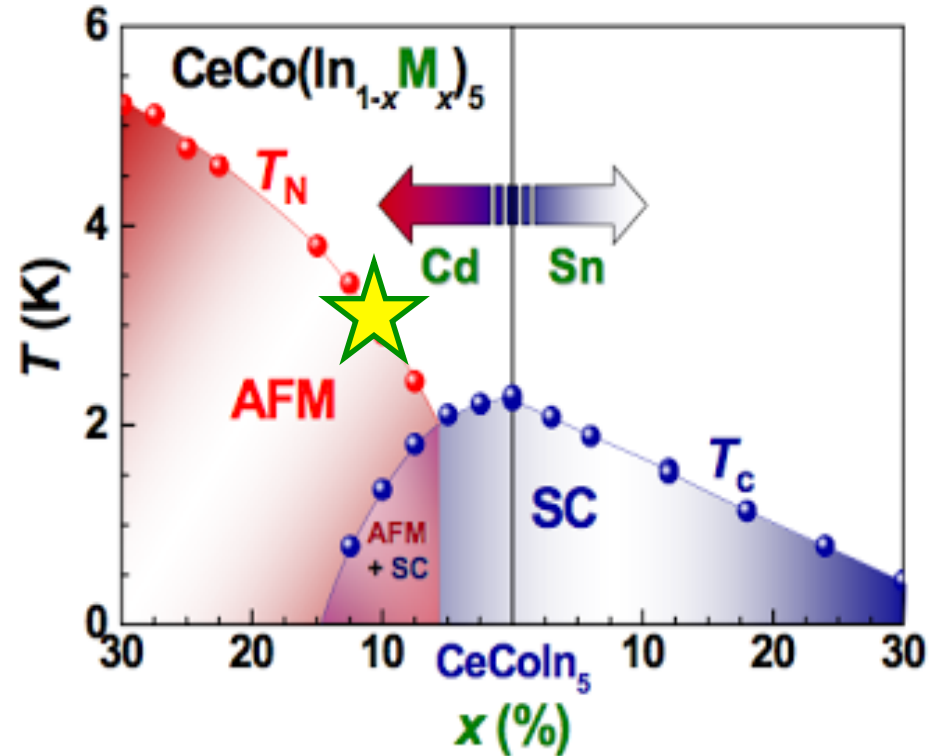
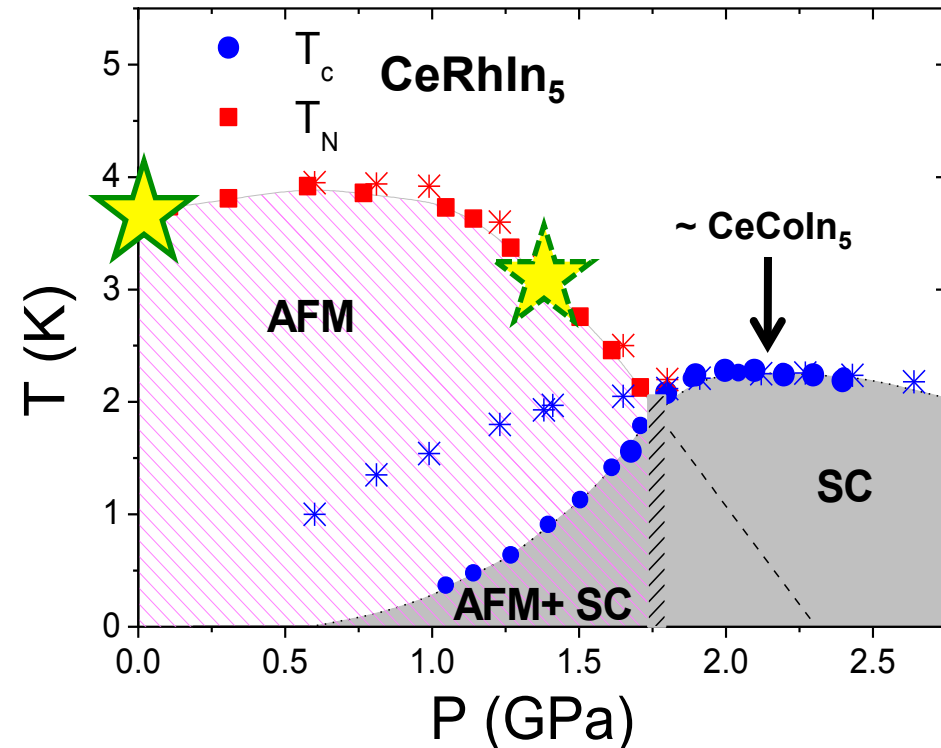
A Tale of Two Dopants

Why doping?

Dopants provides a window into
novel states of matter



How we identified the instability in CeCoIn_5



Cd doping ~ <decreases hybridization>

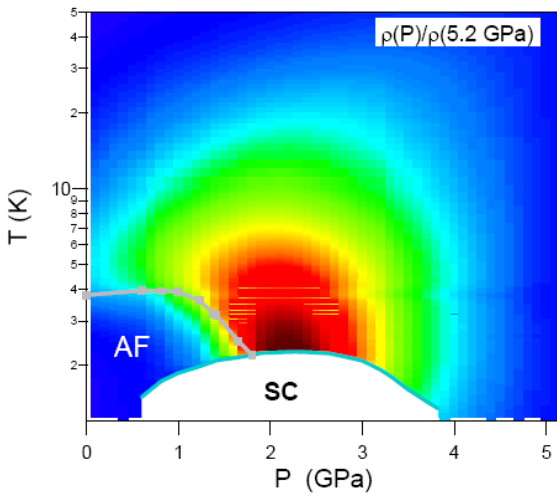
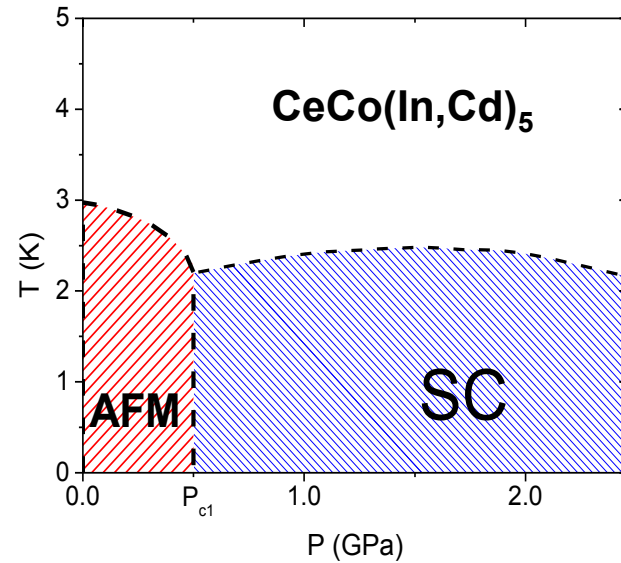
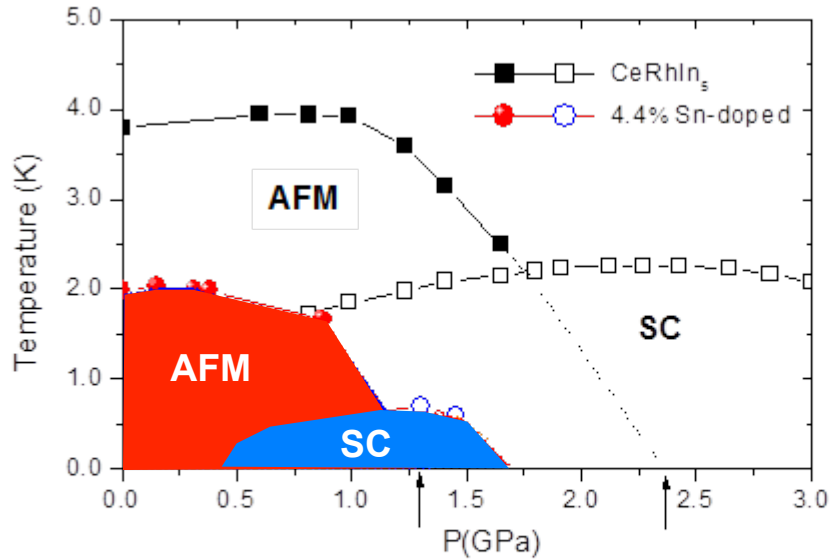
Sn doping ~ <increases hybridization>

CeRhIn_5
(P)

★ $\text{CeRh}(\text{In}, \text{Sn})_5$
(P)

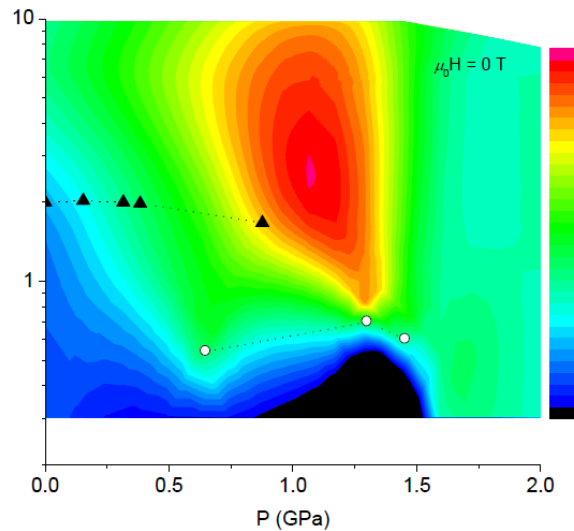
$\text{CeCo}(\text{In}, \text{Cd})_5$
(P)

Cd versus Sn doping



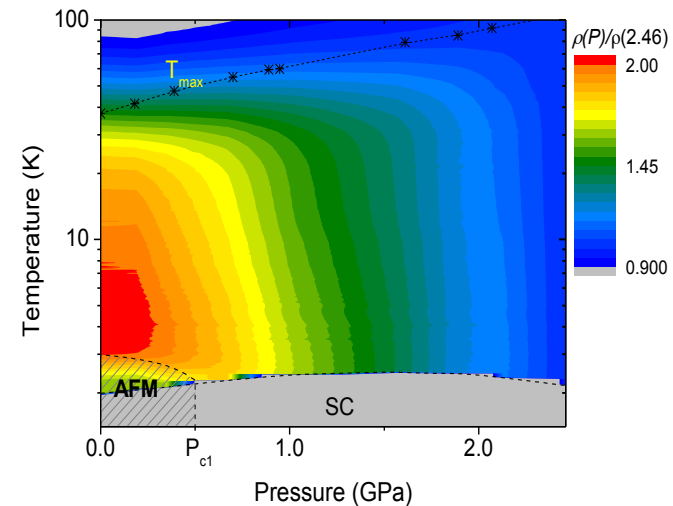
CeRhIn_5

T. Park, et al. Nature '08



$\text{CeRh}(\text{In},\text{Sn})_5$

S. Seo, et al. Nat. Comm. '15



$\text{CeCo}(\text{In},\text{Cd})_5$

S. Seo, et al. Nat. Phys. '13

Cd versus Sn doping

Cd doping:

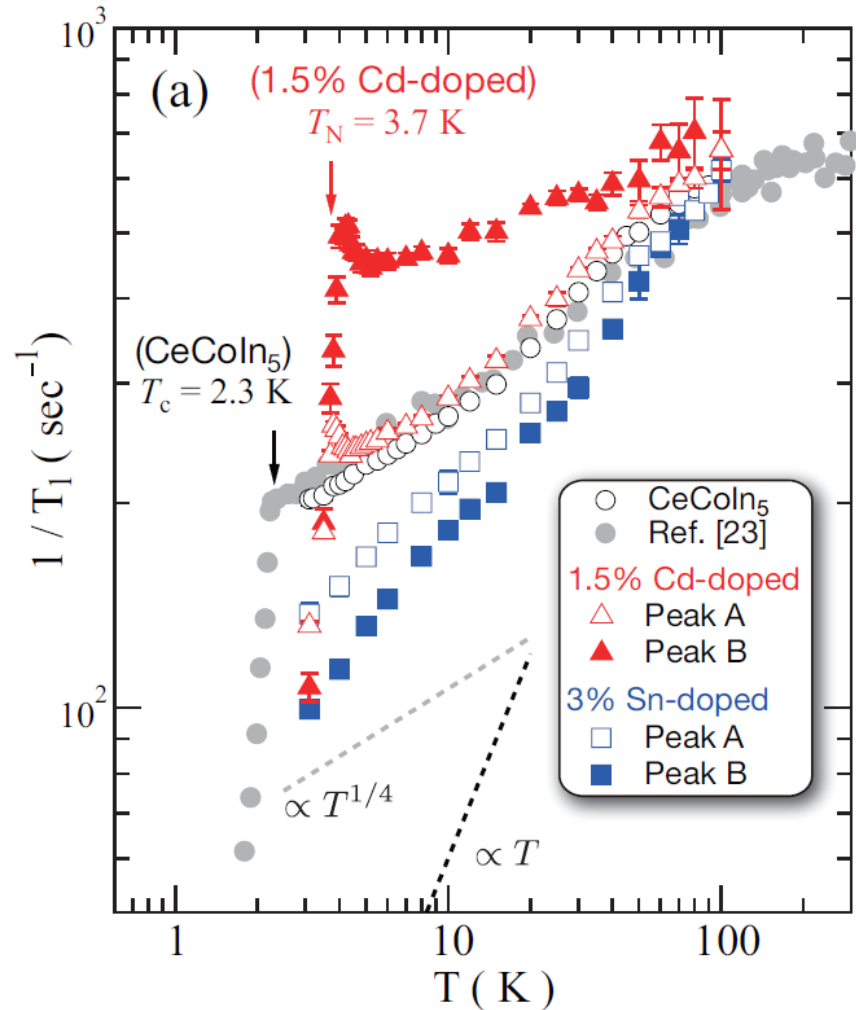
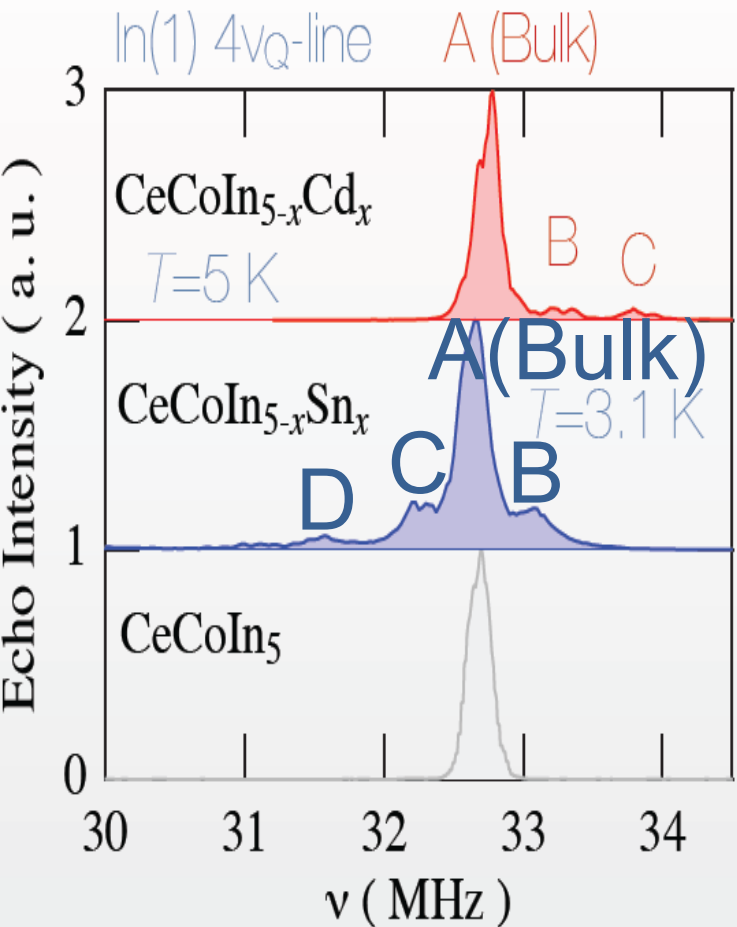
- **Decreased hybridization**
- **Small Tc suppression**
- **Signature of QCP disappears.**

copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922
silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76
gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98

Sn doping:

- **Increased hybridization**
- **Larger Tc suppression**
- **Signature of QCP remains.**

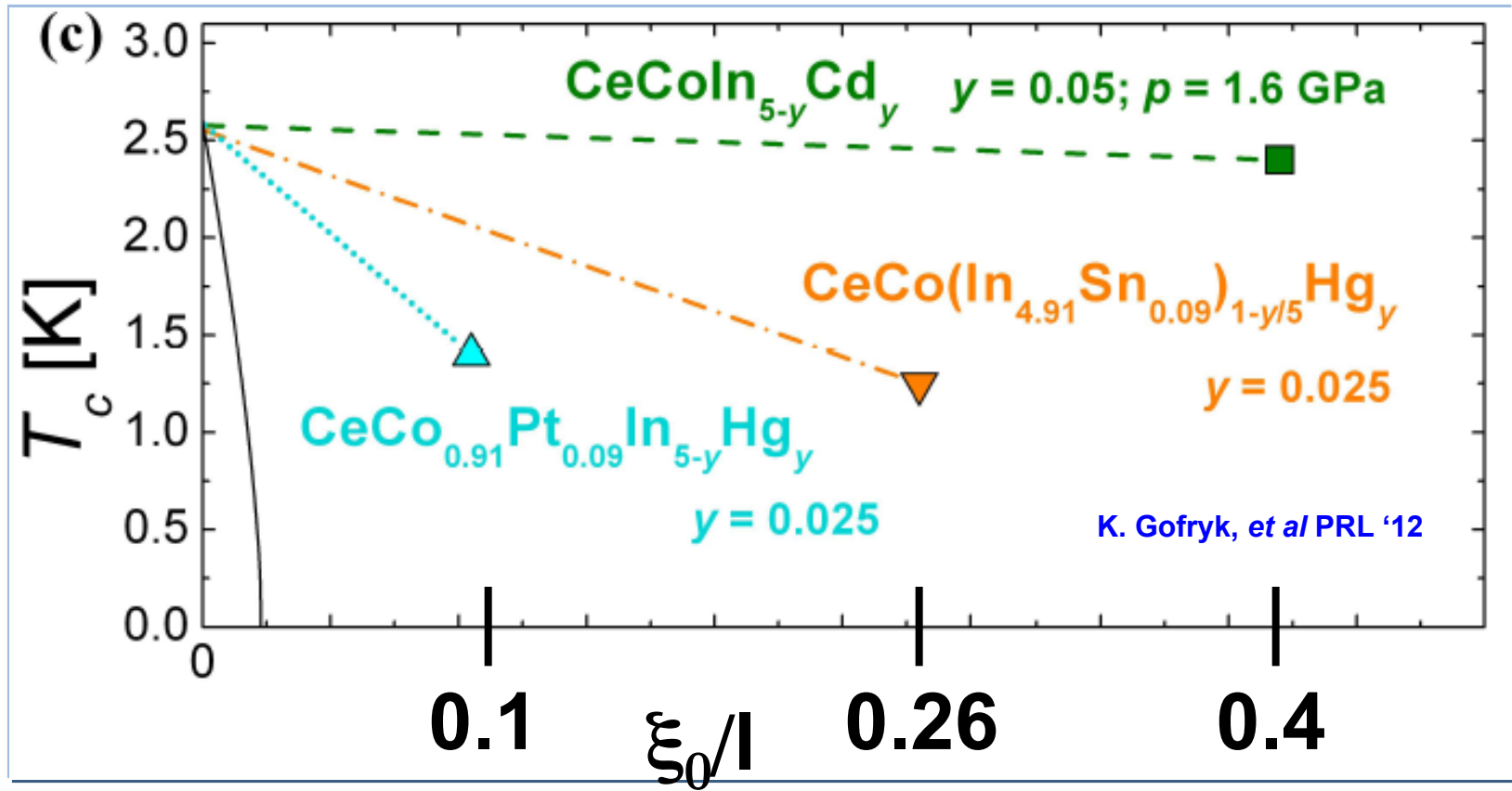
NMR



Cd = “AFM droplets”

Sn ≈ homogeneous

Robustness to impurity scattering: CeCoIn_5



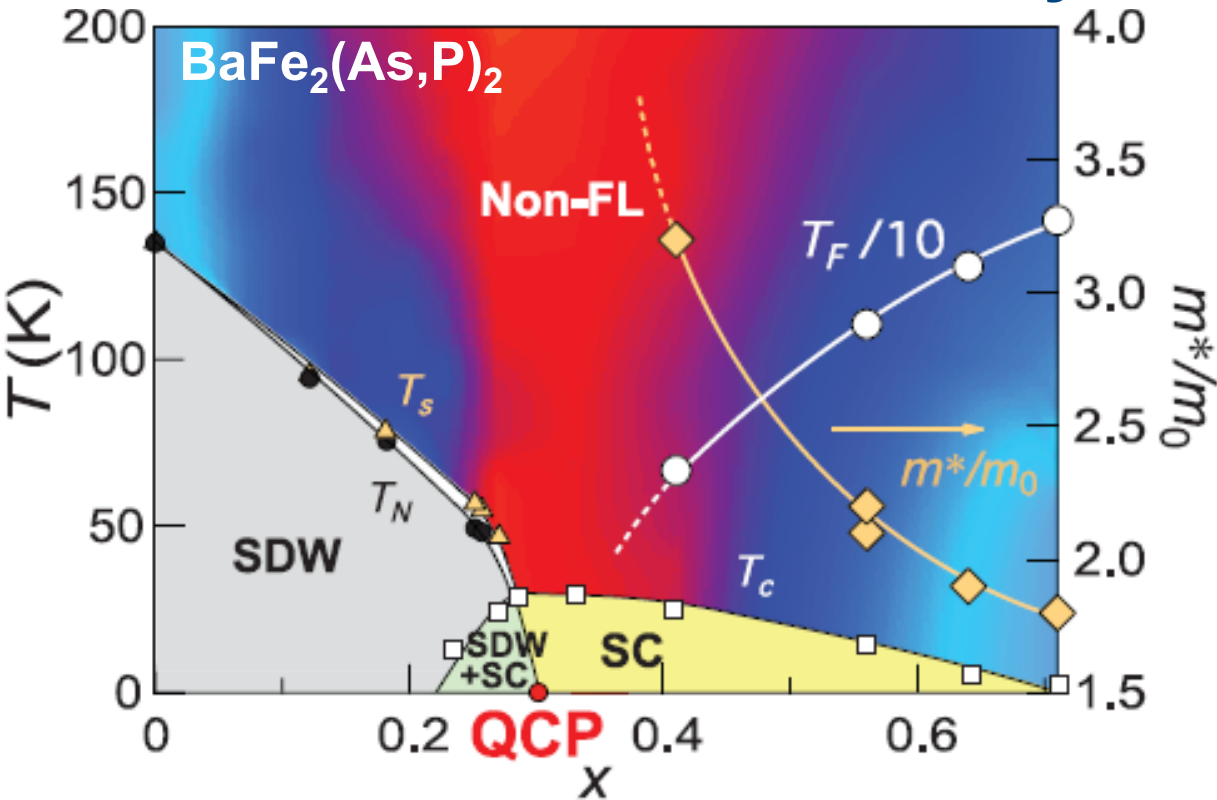
Little doubt that this system is $d_{x^2-y^2}$. Robustness likely due to strong coupling and extreme multiband.

Are inhomogeneous dopants less pair-breaking than homogeneous ones?

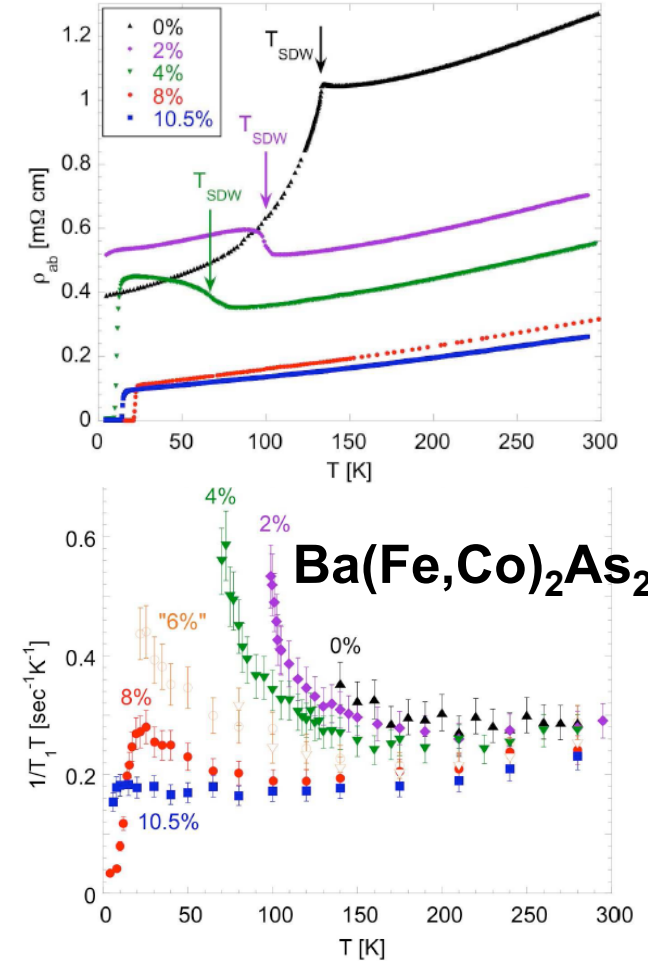
Are filled shells less pair breaking (ie. Cd and Zn)?

Inhomogeneity can obscure signatures of criticality!

Quantum Criticality in Pnictides



K. Hashimoto, et al. Science '10



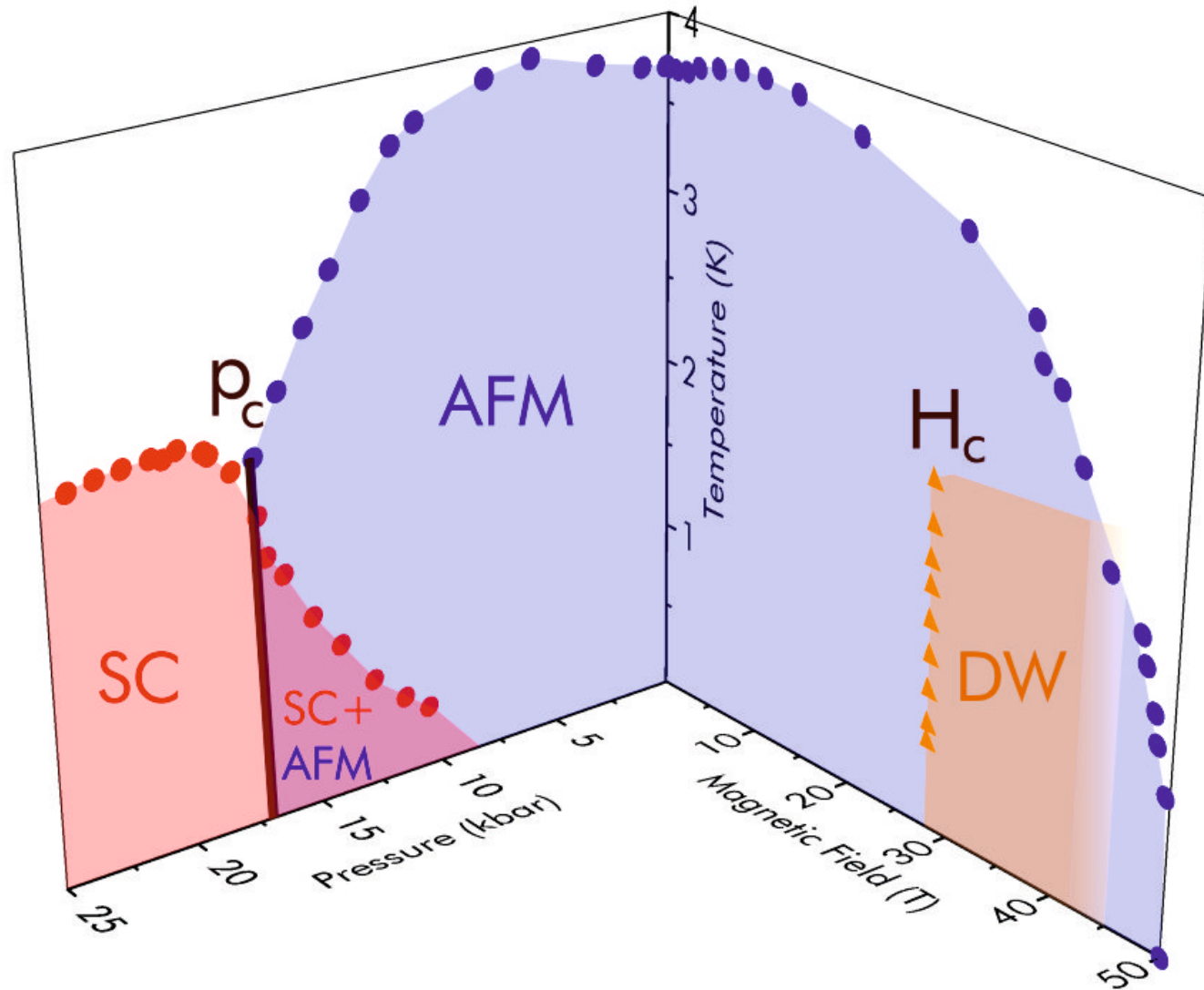
F. Ning, T. Imai, et al. JPSJ '09

❖ QC not always so apparent in pnictides (QC scaling removed by disorder?)

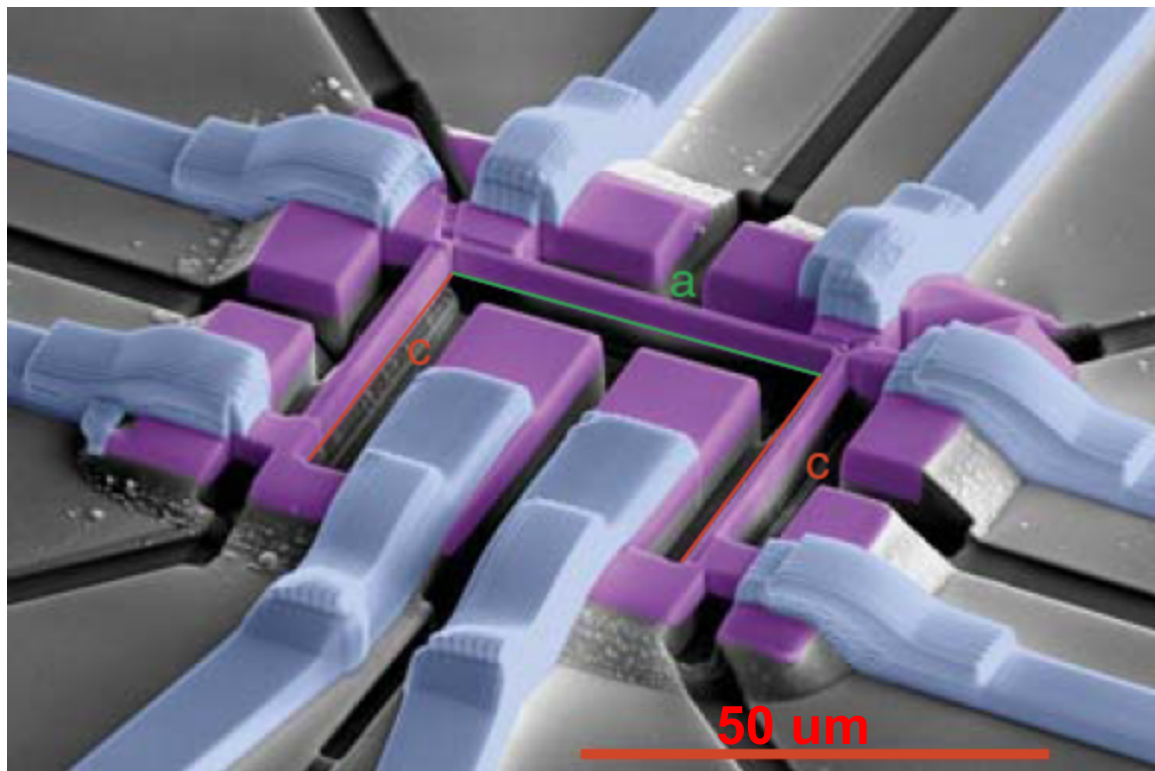
❖ SC still robust.

Accessing the AFM QCP with magnetic field

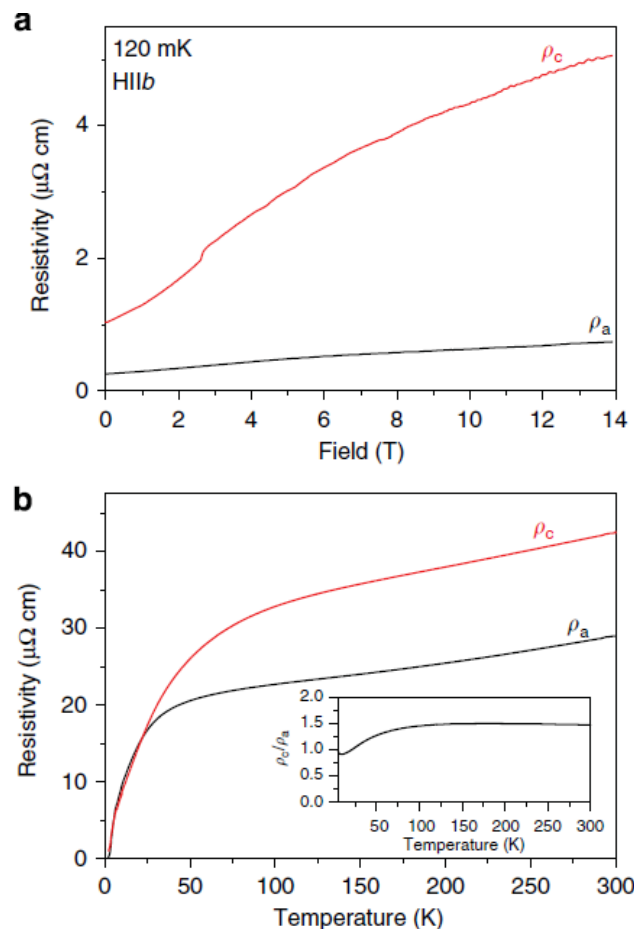
A field induced density wave in CeRhIn₅



Microstructured CeRhIn₅

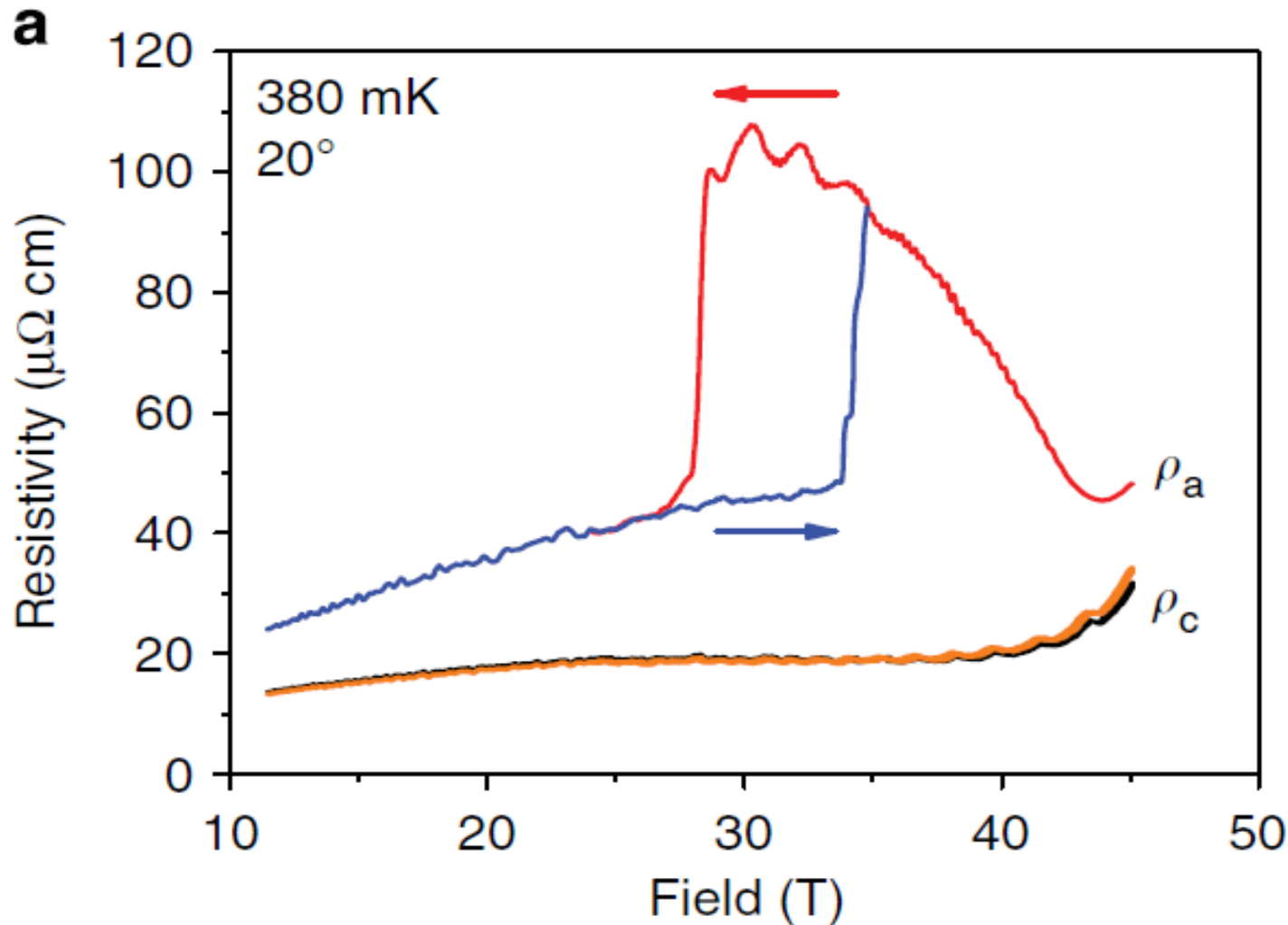


- ❖ Enables magnetoresistance at high fields
- ❖ High current densities possible
- ❖ Transport anisotropy of small crystals



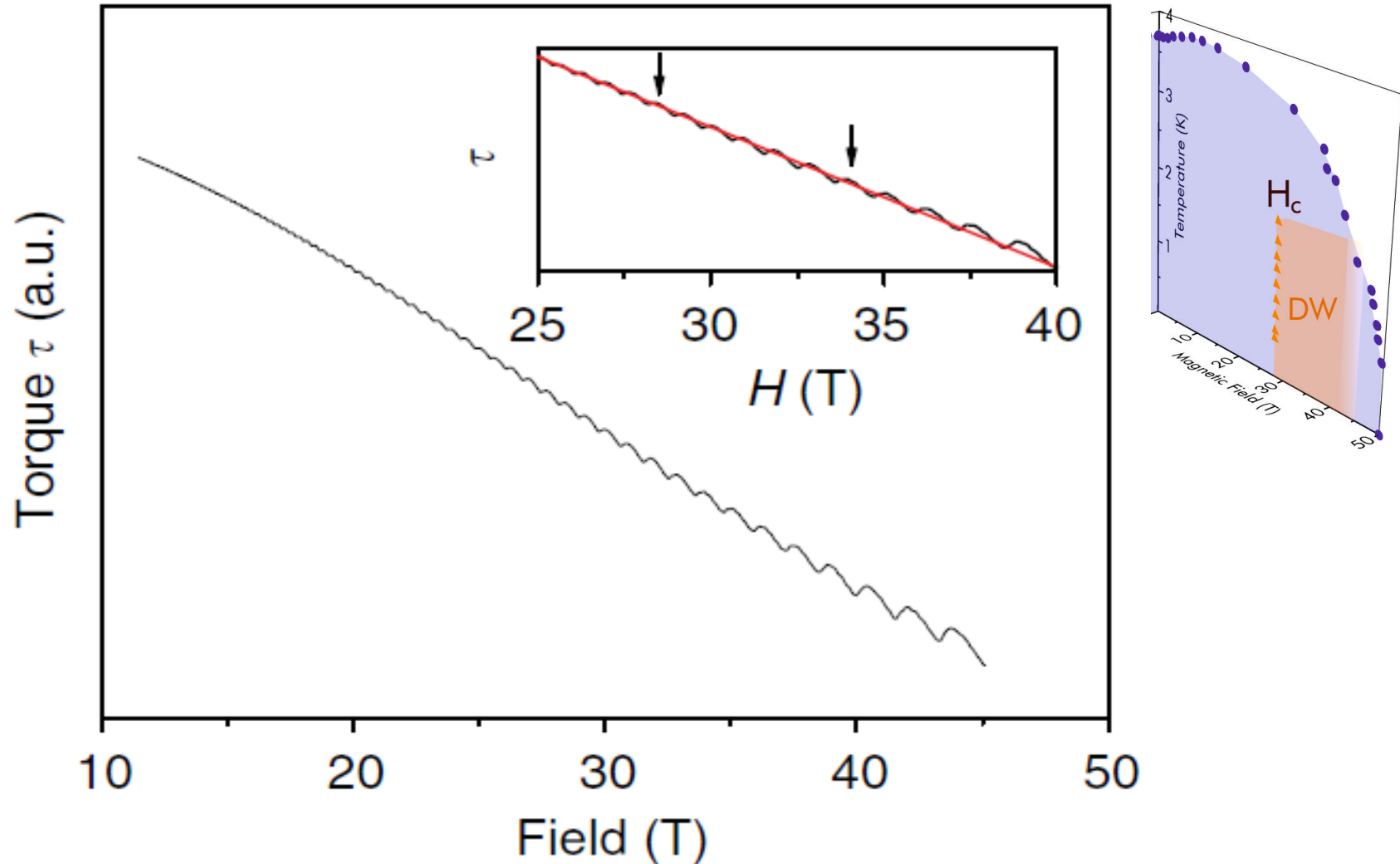
RRR \sim 260

A field induced density wave in CeRhIn_5



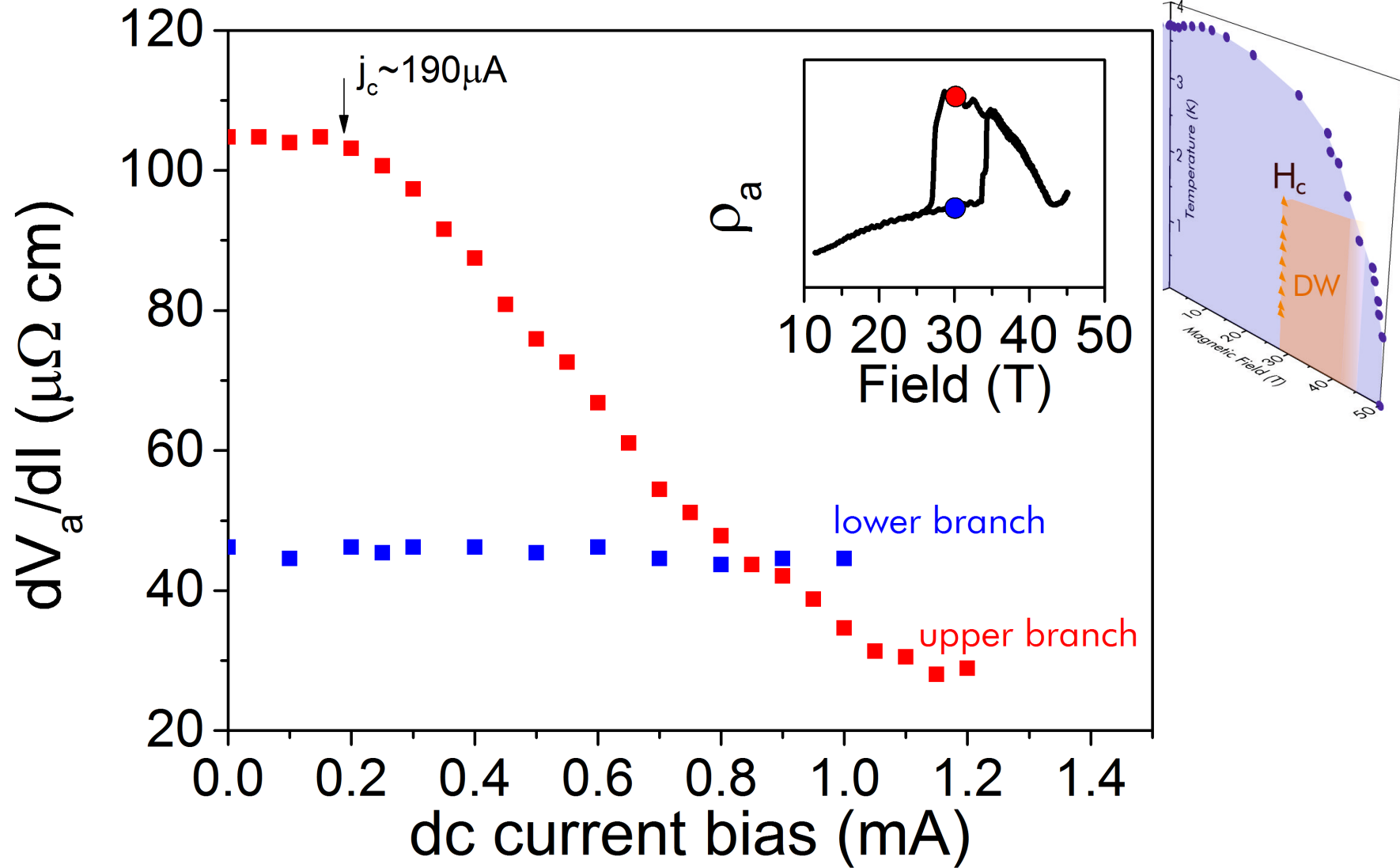
- ❖ Field induced transition within the AFM state
- ❖ Hysteresis vanishes in pulsed fields.

A field induced density wave in CeRhIn_5



- ❖ Not clearly observed in $M(H)$ or $R_c(H)$
- ❖ Small fraction of the Fermi surface participates

A field induced density wave in CeRhIn₅

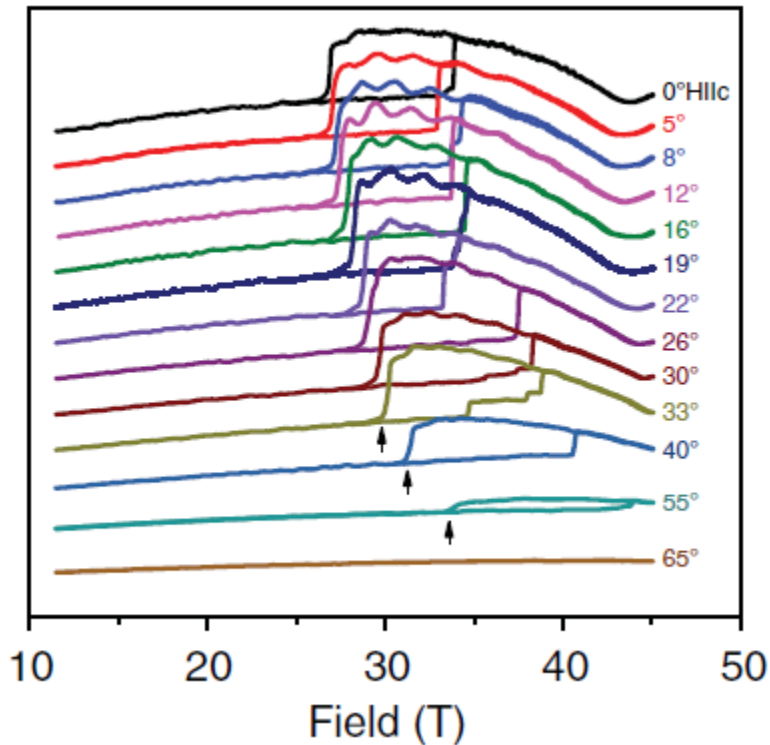


❖ I-V curves resemble CDW systems

Angular dependence of the density wave state

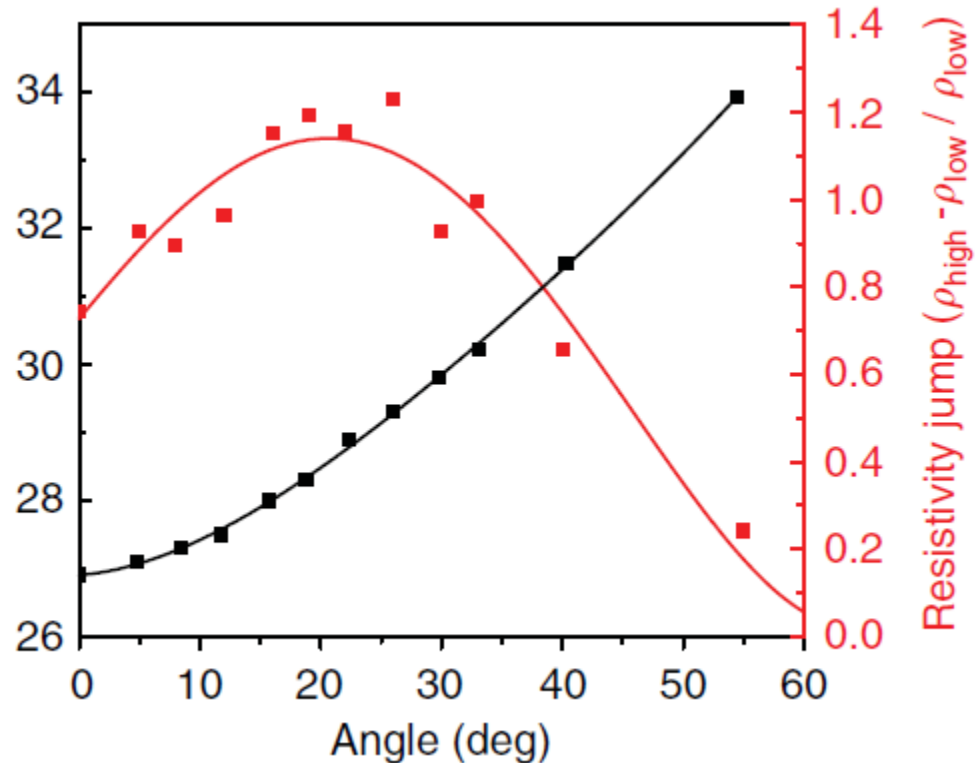
a

Resistivity ρ_a (offset)



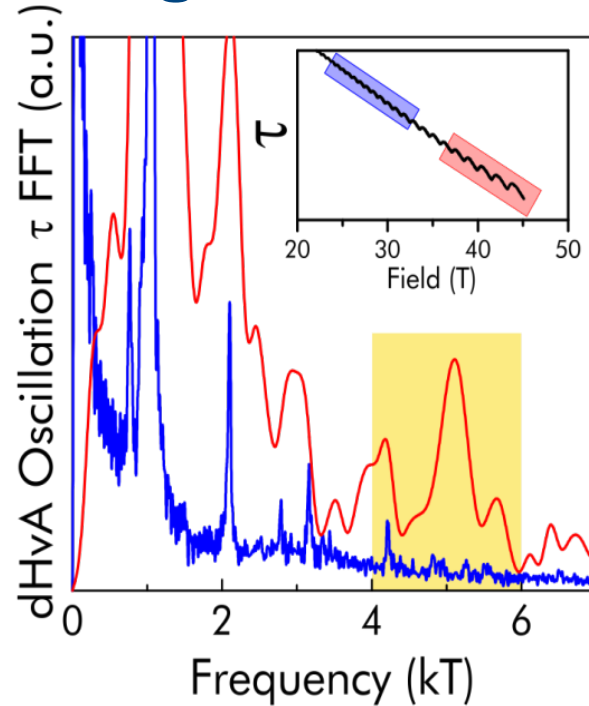
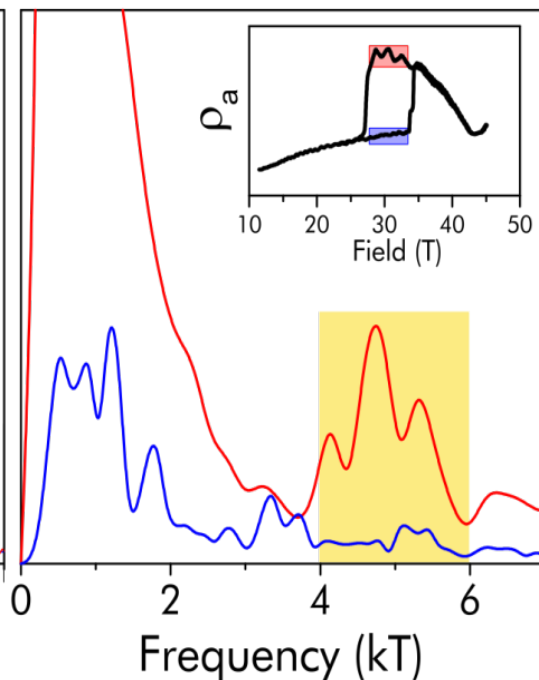
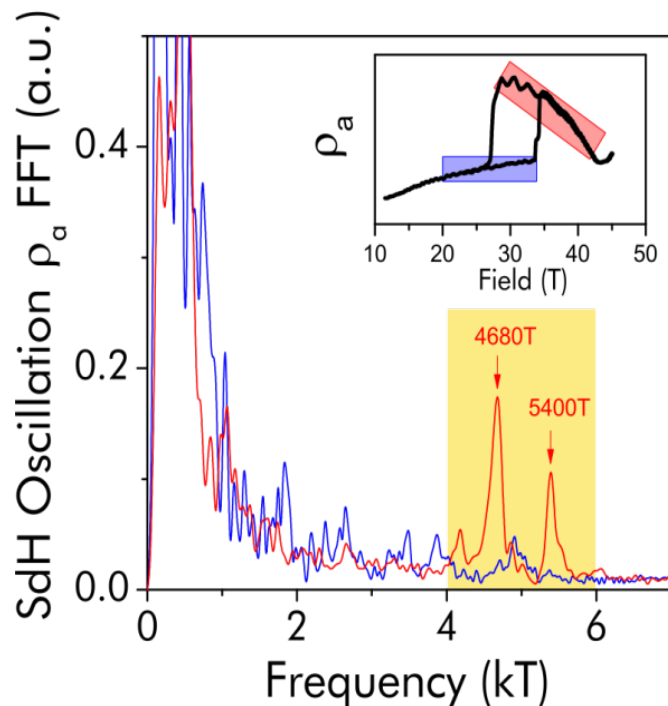
b

Transition field H (T)

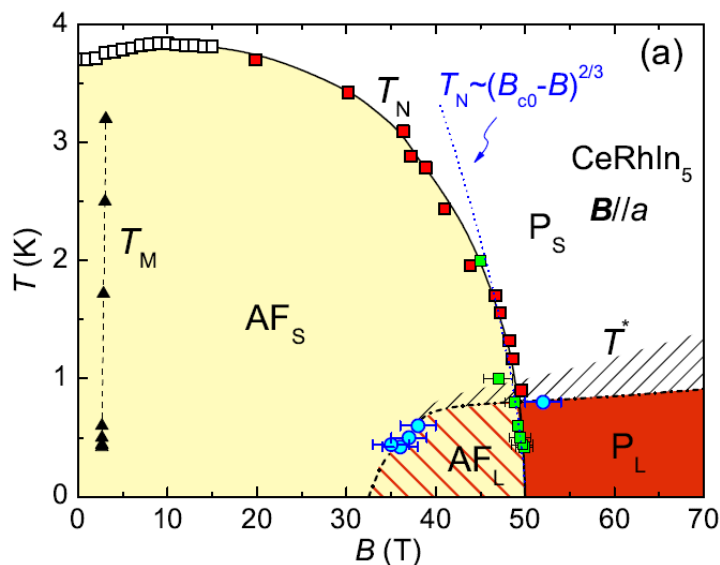


❖ Pushing field into the ab-plane makes the density wave formation energetically unfavorable.

Fermi surface topology change

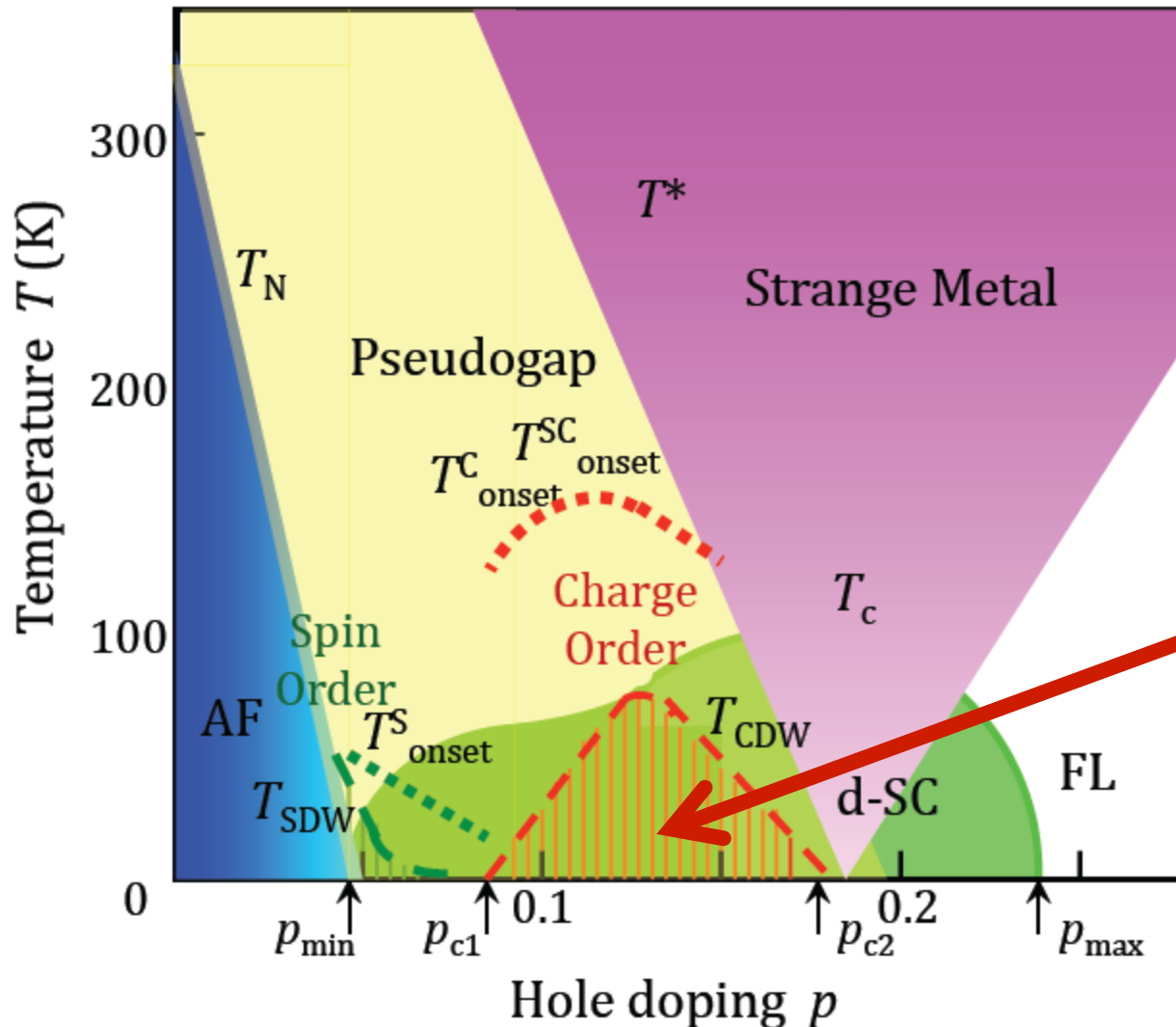


P. Moll, et al. Nat. Comm. (in press)



L. Jiao, et al. PNAS (2015)

Competing Phases

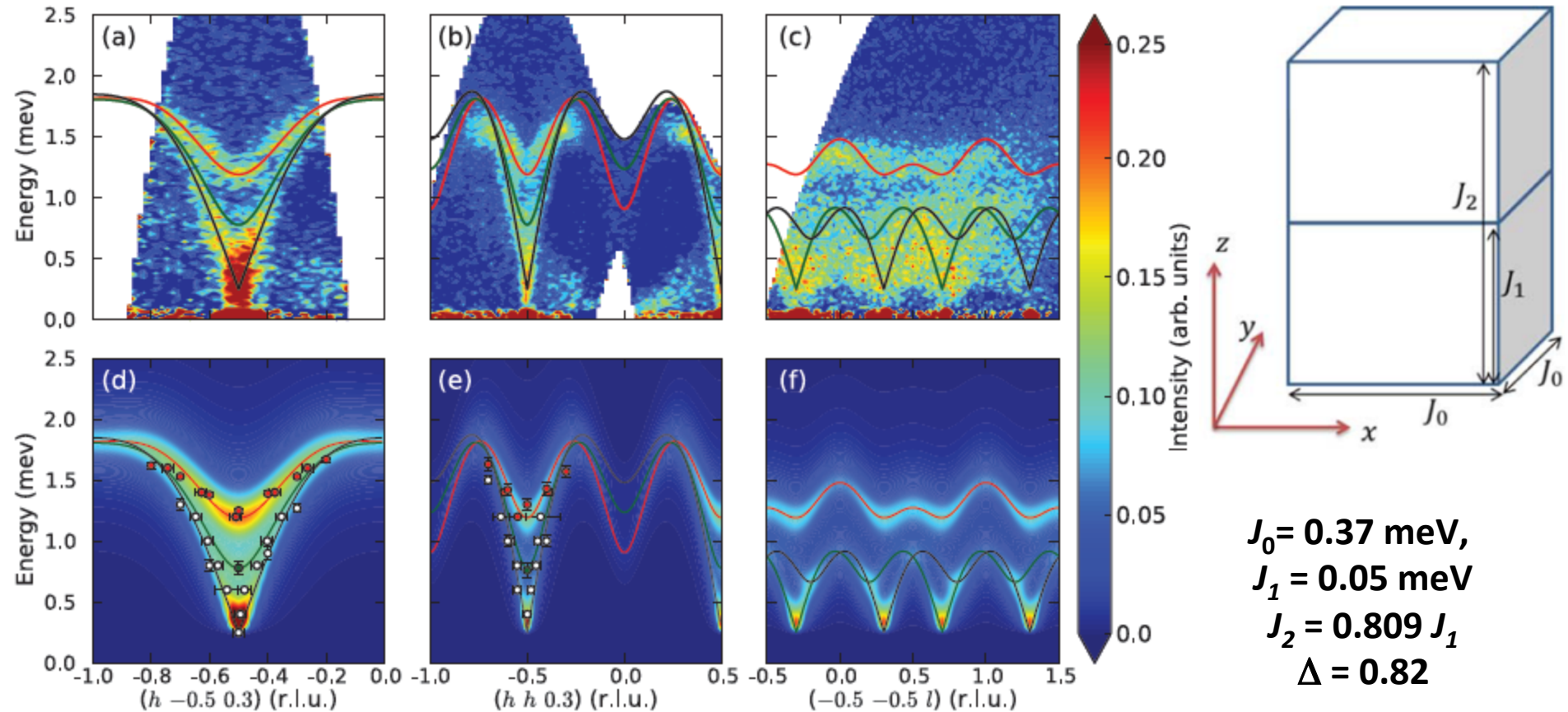


B. Keimer, et al.
ArXiv: 1409.4673

A field induced
density wave

Anomalous transport with H//ab

Spin Waves in CeRhIn₅



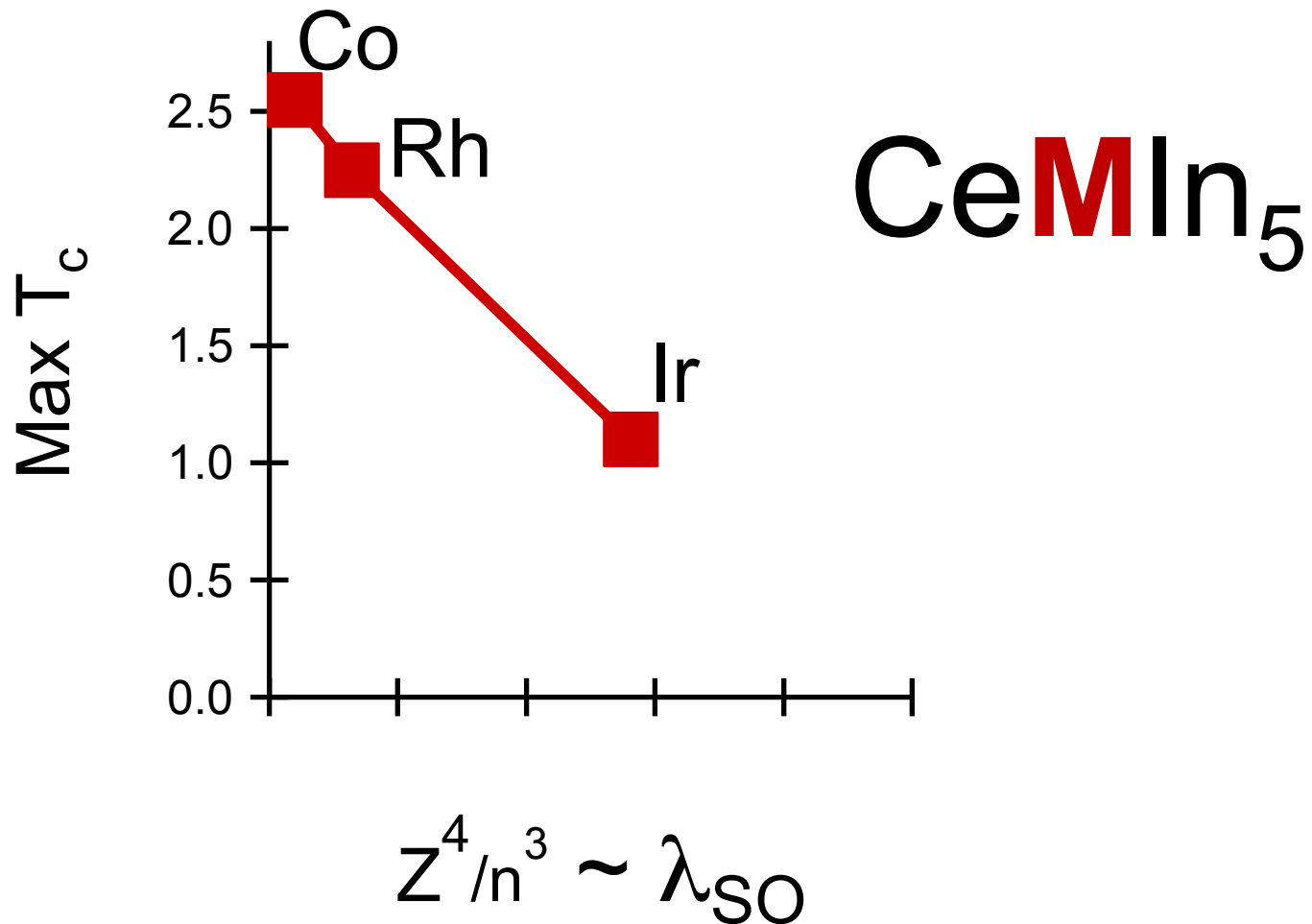
$$\mathcal{H} = \sum_{ij} [J_{ij}(n_i^x n_j^x + n_i^y n_j^y) + \Delta J_{ij} n_i^z n_j^z]$$

The existence of a spin gap, $\Delta_{\text{sg}} = 0.25$ meV, is unexpected for the ordered $\mathbf{Q} = (\frac{1}{2}, \frac{1}{2}, 0.297)$ moments.

CeRhIn₅ is a frustrated system along the c-axis

Spin-Orbit Coupling

How does Spin-Orbit coupling influence T_c ?



Summary

- **two non-magnetic dopants (Cd and Sn) produce dramatically different responses.**
 - **Inhomogeneity can have weaker pair breaking effects**
 - **Can also disguise signatures of quantum criticality**
- **Field Induced Density Wave in CeRhIn5 under applied magnetic field**
- **How does spin-orbit coupling influence T_c ?**

